# Submicron-Long HTS Hot-Electron Mixers

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**Abstract—We have measured the device length and temperature dependence of the intermediate frequency (IF) bandwidth and noise of hot-electron bolometer (HEB) mixers made from a high-$T_c$ superconductor. Mixer devices with lengths (L) between 50 nm and 1 μm were fabricated from 25 - 35 nm thick YBCO films on MgO and sapphire substrates. Bandwidth measurements were done using signal and local oscillator (LO) frequencies in the range 1-20 GHz. At low operation temperatures the IF bandwidths were about 100 MHz and several 100 MHz for devices on MgO and sapphire, respectively. At higher operation temperatures, where self-heating disappeared and flux-flow effects define the shape of the IV characteristic, the measured IF bandwidth increased significantly. The temperature and IF dependence of absolute conversion efficiencies determined from noise measurements are in good agreement with the bandwidth data. At 2.7 GHz LO frequency the single-side-band mixer noise temperatures of a 50 nm long HEB on MgO was about 8000 K.**

## I. Introduction

The hot-electron bolometer (HEB) mixer made from a high-$T_c$ superconductor (HTS) was introduced recently as a competing alternative to a Schottky-diode mixer. The HTS HEB mixer would require 100-times less LO power and thus would be a desirable candidate for long-term atmospheric remote-sensing and planetary missions. The required operating temperatures between 65 K and 75 K can be achieved with available space-qualified coolers.

The HEB mixer consists of a small volume of HTS material between normal metal contacts (Fig. 1). Electrons in the volume can be heated by absorbed RF radiation and transport current. Nonequilibrium "hot" electrons (e*) transfer their energy to the lattice (ph*) during a very short electron-phonon relaxation time $\tau_{e\text{-}ph}$, which is about 1-2 ps at 80-90 K in $YBa_2Cu_3O_{7-\delta}$ (YBCO) [1-3]. The performance of the mixer depends strongly on the total thermal conductance for heat removal from the phonon sub-system. Heat can be removed by escape of the phonons to the substrate ($\tau_{es}$) or, as suggested in [4], by diffusion of phonons to the normal metal contacts ($\tau_{diff}$). Modeling of the performance of HTS HEB mixers showed that the increased thermal conductance provided by phonon diffusion would result in significantly larger band widths at IF's dominated by phonon processes, and lower noise temperatures at IF's dominated by hot-electron effects. In addition, the IF response would depend strongly on the micro-bridge length [4]. In order to make phonon diffusion a dominant thermal process, submicron device lengths are required.

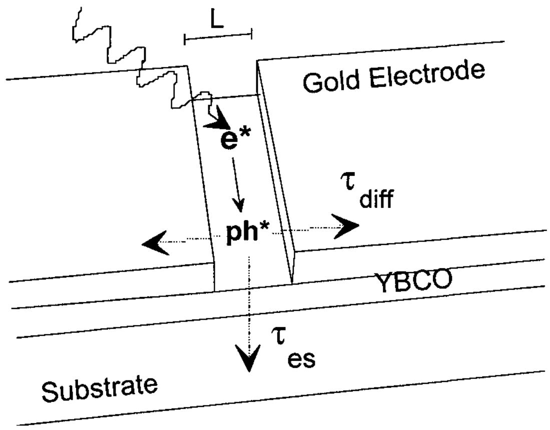


Fig. 1: Schematic of a HTS hot-electron bolometer mixer.

Heat removal through the film-substrate boundary is determined by the thermal boundary resistance ($R_{bd}$) and the heat diffusion in the substrate. Two substrates with good dielectric properties and high thermal conductivity on which high quality HTS films can be grown are magnesium oxide (MgO) and sapphire. MgO provides a low $R_{bd}$ of about $5.3\times10^{-4}$ K cm$^2$/W, while $Al_2O_3$ gives $1.1\times10^{-3}$ K cm$^2$/W [5]. The perovskite-like substrates $LaAlO_3$, $SrTiO_3$ and $YAlO_3$ are less favorable due to their dielectric and thermal properties.

The goal of our work was to fabricate submicron-long YBCO HEB mixers on MgO and sapphire substrates and to determine their intrinsic thermal relaxation times as inferred from the 3-dB IF bandwidth. Additionally, noise measurements at low frequencies were done to provide data on the absolute conversion efficiency and on the LO pumping level required to minimize the mixer noise temperature.

## II. Sample Fabrication

For the fabrication of HEB mixers, YBCO films with thickness of about 25-35 nm were grown on MgO and sapphire substrates using the laser deposition method. On sapphire substrates, a 30 nm $CeO_2$ buffer layer was used between the substrate and the YBCO film. Inductive $T_c$-

Manuscript received April 30, 1999.
This work was supported in part by NASA through the JPL Director's Research and Development Fund and Office of Space Science. Funding for O. H. was provided by the HSP III program of the German Academic Exchange Service (DAAD). Email: o.harnack@fz-juelich.de

measurements showed critical temperatures of 89-90 K for YBCO films on sapphire substrates and 84-86 K for films on MgO substrates with transition widths <2K for both substrate types. After patterning the films into 1 μm wide microbridges integrated with bow-tie antennas, a small-area window (50 nm to 500 nm length) was defined across the bridge using e-beam lithography. After removing the gold layer from the window using the ion beam etching (IBE) method, a $SiO_x$ protection layer was deposited by thermal evaporation.

## III. BANDWIDTH MEASUREMENTS

### *A. Measurement setup and technique*

The measurement system was recently described in detail in [6]. Two sweep oscillators in the frequency range 0.1-26 GHz were used as LO and signal source respectively. The downconverted signal in the range 10 MHz to 10 GHz was directly measured by using a spectrum analyzer. For the bandwidth measurement the LO signal power was adjusted to maintain a constant bias point.

### *B. IF characteristics of devices on MgO*

As shown in Fig. 2, the IF bandwidth of a 50 nm long HEB mixer on MgO depends strongly on the temperature. The IF bandwidth at 50 K was about 100 MHz, increasing to about 2 GHz as the temperature was raised to 83 K. At the same time the conversion efficiency at low IF dropped by several dB (data at 50 K and 62 K should not be included in this direct comparison, since the available LO power was not sufficient to pump the device optimally. Thus the optimal conversion efficiency was probably several dB higher). However, the conversion efficiency at 73 K and 1 GHz IF is about 5 dB higher than for this IF at 65 K.

At the lowest temperature, we clearly see a –20 dB/dec slope at IF>100 MHz and the hot-electron plateau starting around 2 GHz. This device behavior at low temperature is well-characterized by the two-temperature model [7]. Measurements with 200 nm and 400 nm long devices gave very similar results and the theoretically predicted $L^{-2}$-dependence [5] of the IF bandwidths was not observed. The current-voltage characteristics (IVC) show that self-heating effects are present at 50-65 K and, as the temperature becomes closer to $T_c$, flux-flow-like rounding starts to dominate the shape of the IVCs. Flux-flow effects can provide nonlinearities [8], which possibly generate an IF response in addition to the hot-electron mixing response and effectively extend the IF bandwidth as seen at T>70 K. However, it has been shown that the nonlinearity due to flux creep which is the dominant source of d.c. resistivity in the superconducting state, becomes unimportant as the operating frequency exceeds the depinning frequency, which is in the range 10-100 GHz at temperatures close to $T_c$ [8]. We also performed IF bandwidth measurements at 100 GHz and 300 GHz. The results indeed showed that the large IF bandwidth seen at high temperatures (Fig. 2) revert to the low-temperature IF bandwidth as the operating frequency increases above about 100 GHz [6].

### *C. IF characteristics of devices on $CeO_2$/sapphire*

A 50 nm long HEB mixer on $CeO_2$ showed higher IF bandwidths and a quite different scaling of the IF response with temperature. (Fig. 3, the data were averaged and the curves were offset relative to each other for better visibility). At low temperature, the bandwidth is 450 MHz and increases to 2.4 GHz at 83 K. A clear roll-off with a –20 dB/dec slope starting at IF>1.5 GHz is observed over the whole temperature range. A two-temperature model fit to the roll-offs would give a even weaker temperature dependence. Measurements with 80 nm and 300 nm long devices showed a similar behavior. Again, no $L^{-2}$-dependence of the IF bandwidths was observed. In contrast to the case MgO, the

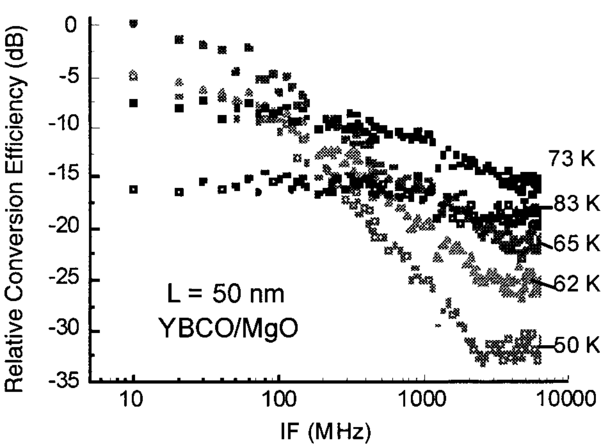


Fig. 2: IF response of a 50 nm long HEB mixer on MgO, measured at different temperatures.

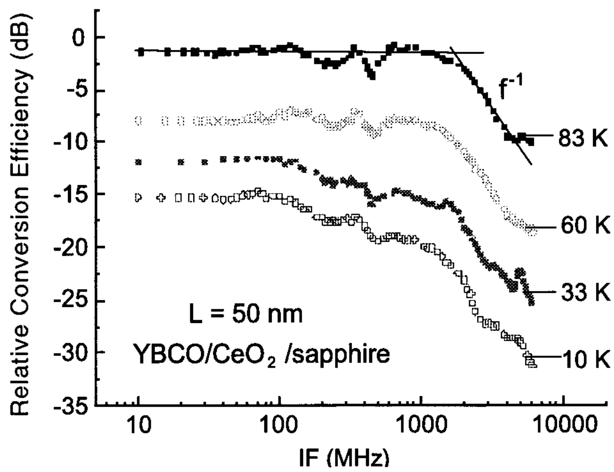


Fig. 3: IF response of a 50 nm long HEB mixer on $CeO_2$/sapphire measured at different temperatures

conversion efficiency did not change significantly with temperature.

## IV. Noise Measurements

### *A) Setup*

Noise measurements were done by using a calibrated HP noise diode as a signal source. The effective temperature $T_N$ of the diode signal was 1100 K at the mixer port and the receiver noise temperature was calculated by using the Y-factor method. The LO frequency was chosen to be 2.7 GHz in order to keep the technical requirements simple. A broadband 10 MHz-1 GHz amplifier was used to amplify the IF signal and different bandpass filters were used to define the IF bandpass for the noise measurements.

### *B) Results*

Figure 4 shows the result of the noise measurement at a temperature of 65 K and at an IF of 120 MHz. After correcting the data for the IF-system noise contribution, the single-side-band (SSB) mixer noise temperature was about 8000 K and the SSB conversion efficiency $\eta$ at the same bias point was -9.5 dB. In order to obtain the lowest noise temperature, the LO power had to be increased up to a level where the hysteresis due to self-heating effects was suppressed. Decreasing of the LO power level resulted in a significant in-crease of the output noise and smaller Y-factors. Table I shows the results of noise measurements at different temperatures and IF frequencies. At the low IF a decrease of $\eta$ of about 2.1 dB can be seen as the temperature is increased from 65 K to 70 K. This drop qualitatively agrees with the IF characteristics shown in Fig. 2. At the same time, the mixer noise temperature increases slightly with temperature.

Keeping the temperature at 65 K we note that $\eta$ drops about 4.4 dB as the IF changes from 120 MHz to 1 GHz. At 70 K this drop is only about 0.8 dB. This is also in qualitative agreement with the measured IF characteristics. At 65 K the difference in noise temperatures of only 0.8 dB suggests that the mixer noise bandwidth is larger than the signal bandwidth. The mixer output noise is quite constant with temperature for an IF of 1 GHz but increases remarkably with decreasing temperature for an IF of 120 MHz, which suggests stronger mixing performance.

TABLE I

RESULTS OF NOISE MEASUREMENTS WITH A 50 NM HEB ON MgO

| IF [MHz] | $T_{MIX}$ (65 K) [K] | $\eta$ (65 K) [dB] | $T_{MIX}$ (70 K) [K] | $\eta$ (70 K) [dB] |
|---|---|---|---|---|
| 120 | 8000 | -9.5 | 8600 | -11.6 |
| 1000 | 9700 | -13.9 | 6650 | -12.4 |

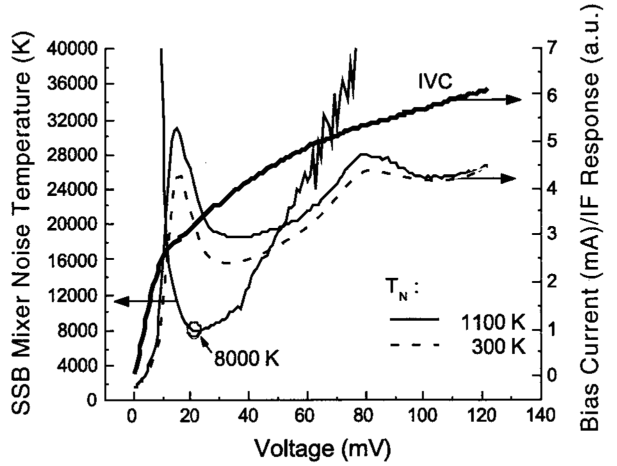


Fig. 4: Noise measurement using a 50 nm long mixer on MgO at 65 K and $f_{LO}$=2.7 GHz. The IF center frequency was 120 MHz and the filter bandwidth was 100 MHz.

## V. Conclusion

We measured the IF bandwidths of sub-μm long HEB mixers on MgO and $CeO_2$/sapphire substrates. An $L^{-2}$ dependence of the IF bandwidth was not observed for our type of device geometry. In terms of available IF bandwidth, HEB mixers on $CeO_2$/sapphire are most promising. The SSB mixer noise temperatures are several-times higher than expected if phonon diffusion was present in our mixers. Additional experiments with different device geometries are required to further investigate the missing phonon diffusion.

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